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The use of carbonate nodules as paleoenvironmental indicators is generally based on examples of modern nodule growth. Although nodules are found in both shallow- and deep-water environments, research on their composition, formation, and depositional setting has been limited almost exclusively to shallow depths. The lack of deep-water studies results primarily from the logistical difficulties associated with research below 20–30 m. Consequently, interpretation of fossil deposits containing carbonate nodules may be biased by our lack of knowledge regarding nodule formation in relatively deep-water habitats.

Recent observations of carbonate nodule growth on Florida's outer shelf reveal the processes by which carbonate nodules may form in a relatively deep (35–65 m), quiet-water setting. Observations in situ and examinations of internal nodule structure indicate that encrusting organisms—primarily the foraminifera, Gypsina vesicularis, and various coralline algae genera—grow on a nodule's upper as well as lower surfaces. Nodule formation may therefore be facilitated by slight repositioning rather than complete overturning. On Florida's outer shelf, repositioning of nodules occurs (1) frequently as a result of intense biologic activity at the sea floor, and (2) infrequently as a consequence of physical transport during hurricane-strength storms or periodic surge events.

These findings suggest that in addition to the traditional association with shallow-water habitats and physical turbulence, fossil carbonate nodules may be indicative of a relatively deep, quiet-water setting characterized by persistent bioturbation and occasional near-bottom flow.

INTRODUCTION

Concentrically layered nodules of calcium carbonate are commonly found in both ancient and modern marine deposits (Fig. 1). As analogies to ancient environments, examples of modern nodule formation are an important key to understanding past geologic conditions. However, to accurately assess a depositional environment from the rock record using nodule occurrence, all of the alternative settings and modes of modern growth need to be established. Until recently, nodule growth has been studied almost exclusively in shallow-water environments (Reid and Macintyre, 1988). South Florida's outer shelf offers an opportunity to examine the development of nodules in a relatively deep, quiet-water setting. The presence of calcareous nodules on the outer shelf was noted during a submersible survey in 1981 (Shinn) and a hydrographic study revealed that this area is consistently influenced by only moderate- to low-energy currents (Lee, 1984).

Previous Research

It is generally believed that nodule formation is a result of a two-fold process: 1) encrustation by carbonate-producing or sediment-trapping organisms, and 2) repeated turning of the encrusted surfaces. Previous studies in shallow water show that nodule turning may be facilitated by waves or tidal currents (Ginsburg and Bosellini, 1971), a sloping surface (Boscence, 1983; Littler, 1973) or bioturbation of the underlying sediments by the grazing of herbivorous fish (Glynn, 1974). Proposed yet unconfirmed hypotheses for the turning of deep-water coralline algal nodules (rhodoliths) include occasional storms or increased currents, internal sediment waves, biogenic influence, and lowered sea level (Logan et al., 1969; Boscence, 1983).

Nodules, such as rhodoliths, are classified based on the type of organism which has contributed most to a nodule's carbonate accretion (Table 1). Previous research suggests that the morphology of nodules formed by these organisms may be directly related to the environmental conditions during growth. Study of the rhodoliths in a shallow lagoon in Bermuda (Ginsburg and Bosellini, 1971), illustrated that a rhodolith's gross morphology and internal structure were often a product of the frequency and means by which a nodule had been moved. Rhodoliths were found to be spheriodal and/or ellipsoidal when frequently moved, and somewhat flattened when turned less often (Ginsburg and Bosellini, 1971). Additionally, individual coralline algae genera were found to grow columnarly or branching in relatively sedentary nodules and in laminar layers when moved more often. As a result of infrequent movement,

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FIGURE 1—Distribution of modern and Tertiary rhodoliths, modified after Boscence, 1985.

branching rhodoliths have also been found to exhibit distinct directions in growth (Boscence, 1985). Furthermore, in turbulent conditions, apical growth may become laminar due to the effects of abrasion during vigorous turning (Boscence, 1985). If these patterns hold true for both shallow- and deep-water nodules, then well-preserved fossil examples may contain significant information regarding their original environments of deposition.

Study Area

Florida's outer shelf between 25.6° N and 24.9° N extends seaward from the lower limit of appreciable reef growth (approximately 18 m) to the approximate position of the continental shelf break (90 m, Fig. 2). This outer shelf is characterized by low relief and a gradually sloping surface (1°; Enos and Perkins, 1977). Sediments are coarse- to fine-grained and are often covered with algae and/or an organic film. In addition, patch reefs and outcrops of lithified rock are found scattered along the outer shelf (pers. obs.).

RESULTS

Nodule Morphology and Composition

Using SCUBA, nodule sampling was conducted by repeated, random tossing of a 0.3m^2 quadrat, and collecting those nodules within each quadrat area. A small, scoop-like dredge was used to sample bottom sediments from the surface where depths made the use of SCUBA unsafe. Dredge transects were chosen seaward and halfway between charted reefs. At least two depths were sampled per transect (refer to Fig. 2 for location of transect sites). A total of 206 nodules were collected; for each nodule a weight, size (average diameter), and sphericity was determined (Fig. 3, Table 2). In contrast to the majority of previously studied nodules, the predominant nodule constituents are the encrusting foraminifera, *Gypsina vesicularis*, various genera of coralline algae, and bryozoans (Table 3). Observation in thin section of slabbed, resin-

impregnated nodules confirm that encrusting foraminifera and coralline algae are the primary nodule builders. Without an appropriate term available in the literature, we will refer to these nodules, composed primarily of varying proportions of foraminifera and coralline algae, as "for-algaliths."

As in other types of concretionary growth, nodule layering characteristically surrounds a central nucleus. Identification of nuclei is often difficult or impossible owing to the bioerosion and micritization of a nodule's interior. Coral, bivalves, large *Halimeda* plates, micritized and bored rubble, and coarse-grained sediments were identified as nuclei within sample nodules. In thin-section, coarse sediment nuclei are commonly interwoven with silicious sponge spicules. Aggregates of similiar composition are found *in situ* covered by an orange-colored sponge.

Internal Layering

As suggested in the past, infrequent rolling of nodules may produce layering that reflects extended periods of growth in one or more direction. Photographic enlargements of thin sections were mapped to determine the distribution of layers about a nodule's nucleus, assuming that infrequent rolling and upper surface growth would produce layers that were unevenly distributed about the nucleus. Although some nodules exhibited this uneven growth, an approximately equal proportion (53%) of the nodules exhibited layers that were relatively evenly distributed, almost completely encircling a nodule's circumference.

Live growth was observed on nodules *in situ* or immediately after collection to delineate which nodule surface was the site of encrustation. Determination of the live growth was based on the coloration of surface constituents. *In situ* or immediately after collection, live coralline algae appear various shades of pink, purple or tan; live *Gypsina* appear greenish-tan due to the presence of small dinoflagellates within their tissues. Shortly after removal from seawater these algae are expelled from the foraminifera's tissues, resulting in a whitened color. Qualitative assesment during dives indicated that live growth occurs on all nodule surfaces—upper, lower, and sides. Bleaching, indicative of non-growing or dead surfaces, was consistantly found to occur on nodules partially or completely submerged within the surrounding coarse-grained sediments. Because the only surfaces restricted from encrustation are those actually in contact with the surrounding sediments, only slight repositioning rather than complete overturning is necessary for the development of a nodular form.
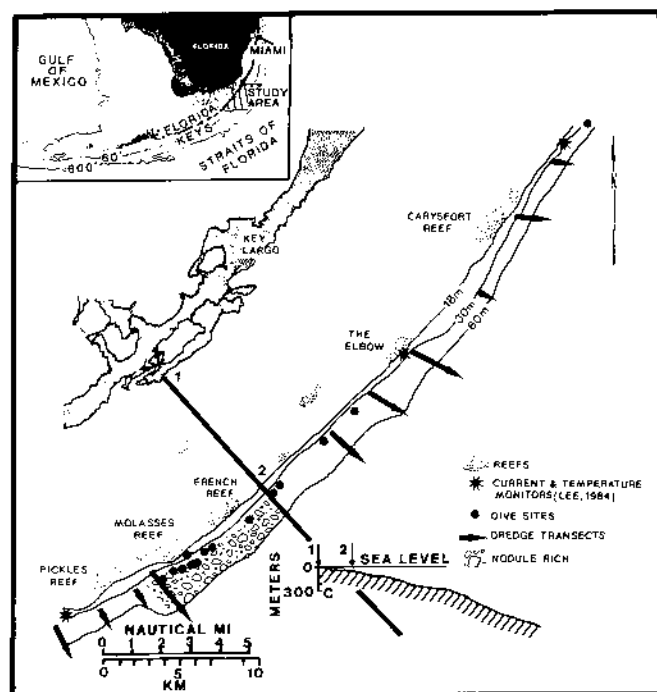
Nodule Distribution

Due to the limitations of time safely on SCUBA at depths greater than 35 m, it is difficult to quantify the distribution of nodule growth or examine its changes with increasing depth, consequently only the general pattern of distribution will be discussed.

Based on the results of dredging, SCUBA, and submersible dives, the region of nodule growth on Florida's outer shelf is shown in Figure 2. Within the zone labeled nodule-rich, between south Molasses Reef and north of French Reef, dredging consistently produced nodules ranging in size from coarse sand to over 9.0 cm in diameter. Nodules were never found shallower than approximately 35 m, nor deeper than 60

TABLE 1—Nodule classification

Organisms	Nodule Term	Author
Coralline Algae	Rhodolith	Ginsburg and Bosellini, 1971
Micro-organisms	Oncoid/Oncolite	McMaster and Conover, 1966
Coral	Corallith	Glynn, 1973
Bryozoans	Ectoproctalith	Dade and Cuffey, 1984
Foraminifera and	"For-algalith"	This study
Coralline Algae		

FIGURE 2—Chart of the study area, showing location, principal reefs, bathymetry, collecting sites, transects, and nodule distribution.

TABLE 2—Nodule morphology

	Range	Average
Nodule size (cm)*	1.7–9.0	3–5
Nodule weight (gm)	3.2–300	20–30
Nodule sphericity**	spheroidal (78%),	ellipsoidal (21%)
	discoidal (4%)	

*Average diameter
**Plotted as a function of S/L, L-I/L-S and $^3\sqrt{S^2/LI}$, where S, I, and L are the short, intermediate, and long diameters, respectively.

TABLE 3—Most common nodule constituents

ENCRUSTING FORAMINIFERA
Gypsina vesicularis
Homotrema sp. (minor)
CORALLINE ALGAE
Lithothamnium sp.
Lithoporella sp.
Tenarea sp.
Peysonnalia sp.
Mesophyllum sp.
Lithophyllum sp.
Archeolithothamnium sp.
BRYOZOANS
Stylopoma sp.
Steginoporella sp.
Hippoporina cleidostoma
Smittina sp.
Schizoporella sp.
Hippopodinidae sp.
Unidentified spp.
SPONGE
Clionidae sp.
Chondrilla nucula
SERPULIDS AND OTHER POLYCHAETES

m. North and south of the nodule-rich zone, dredging recovered only coral rubble, platy corals, coarse-grained sediments, or nothing. Submersible dives along approximately 30 km of the outer reef tract approximately 6 km north of the region shown in Figure 2 found no nodules on the outer shelf.

Observations with SCUBA indicate that for-algaliths are distributed unevenly within the area of nodule growth. Scattered patches of nodule growth contain as many as 45–60 nodules/m² or as few as 3–6 nodules/m².

Sea-floor morphology and nodule distribution on the outer shelf are strongly influenced by the activities of two bottom-dwelling organisms, the echinoderm *Meoma ventricosa*, and the sand tilefish *Malacanthus plumieri*. Nodules are often found in distinct mound-like concentrations, up to 0.4 m in height, scattered over the sea floor (Fig. 4). These nodule mounds are
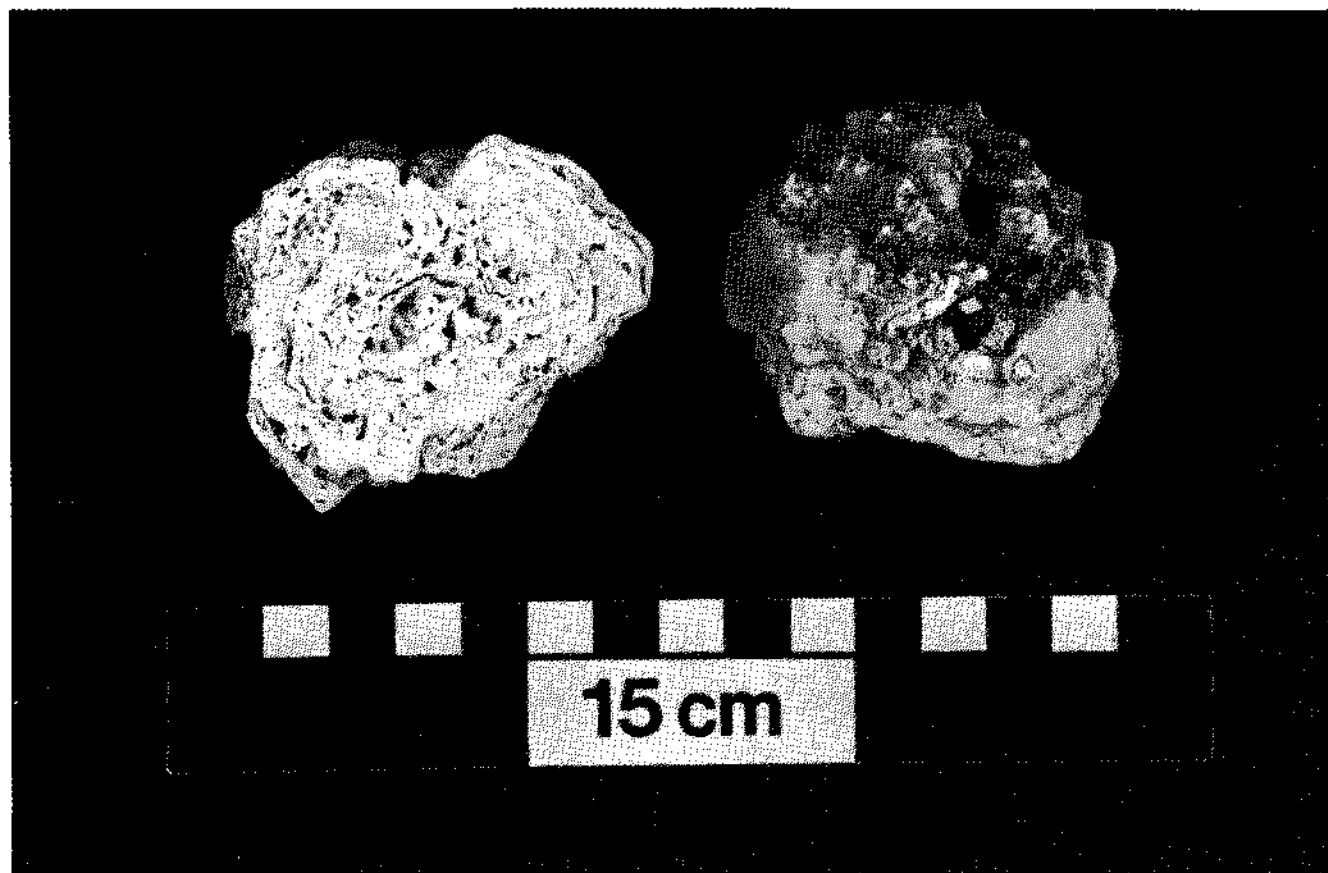
FIGURE 3—Representative nodule, collected at a depth of 36 m, seaward of Molasses Reef. Note concentric layering.

found throughout the nodule-rich zone, with several often occurring within a few meters of one another. The sand tilefish, *Malacanthus plumieri*, is often observed to dive beneath a nearby mound. Previous research indicates that sand tilefish collect coarse-grained to cobble-sized sediments to build protective, mound-like nests (Longeley, 1941). Therefore mound-like concentrations of nodules are presumably sand tilefish nests. Nodules are also found along the margins of numerous sandy trails which often cover the sea floor in an interconnecting mosaic (Fig. 5). Each trail is approximately 12 cm in width and often several meters in length. Upon closer examination, a large, sediment-covered echinoderm identified as *Meoma ventricosa* may be found amidst many of these trails (Fig. 6).

Hydrography

Daily, near-bottom currents on the outer shelf have been determined to generally flow toward the north at average speeds of 5–25 cm/s (Lee, 1984). These currents measured at approximately 2 m above the sea floor over a three year period ranged from 53 cm/s seaward of The Elbow to 22 cm/s south of Pickles Reef (Lee, 1984; Fig. 2). Observations during dives confirm the presence of relatively weak (estimated at less than

FIGURE 4—Mound-like concentration of nodules, 38 m depth, seaward of Molasses Reef. Scale is 15cm.

1 knot) surface and bottom currents, generally flowing to the north. On one occasion when the surface current increased in velocity to an estimated several knots, near-bottom currents
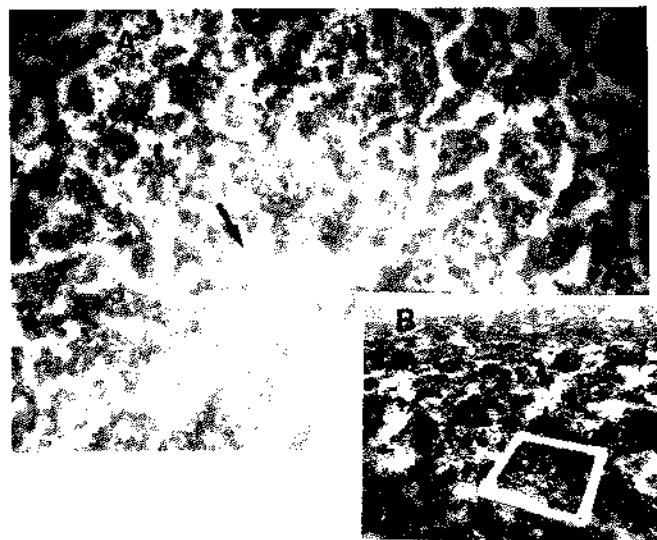
FIGURE 5—A) View from above of abundant, meandering echinoid trails, 38 m depth, seaward of Molasses Reef. Trails are approximately 12–15cm in width. **B)** Seafloor morphology. Arrows indicate echinoid trails; quadrat is 0.3m²
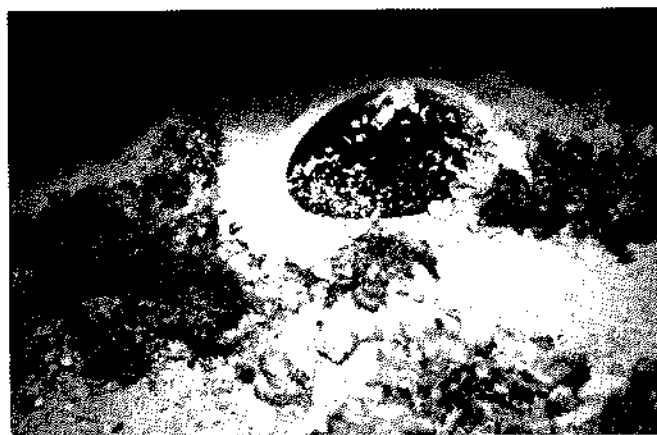

FIGURE 6—The plow-like feeding of the echinoderm, *Meoma ventricosa*, depth is 38 m, seaward of Molasses Reef, echinoid is approximately 14 cm in length.

remained slack (less than 1 knot). No sedimentologic evidence of current activity at the sea floor (i.e., ripples, scours or asymmetric lags) was found at any of the study sites.

Calculations based on previously compiled wind and wave data were made to determine the current strength generated at a depth of 37 m as a result of tropical storms and hurricanes (Appendix). Calculations suggest that tropical storms and hurricanes passing over or near Florida's outer shelf may produce near-bottom currents with velocities of 13 cm/s and 121 cm/s respectively.

DISCUSSION

Processes of Nodule Movement

Two lines of evidence suggest that on Florida's outer shelf nodule movement occurs as a result of infrequent near-bottom flow and frequent bioturbation of the underlying or nearby sediments. Within the area of nodule growth the lack of bedforms indicative of bedload transport (i.e., ripples, scours, or asymmetric lags) suggests that current activity at the sea floor is weak and/or infrequent. The presence of symmetrical fish mounds, undisturbed and numerous shallow foraging trails, and large, articulated *Halimeda* plants also indicates a relatively low-energy environment and infrequent bedload transport. A comparison was made of measured and calculated near-bottom current velocities with the threshold velocity as described by Inman (1949) required to entrain grains comparable in size to the average for-algalith (3–5 cm in diameter). Results suggest that daily currents and tropical storms are incapable of moving the majority of for-algaliths. However, according to Inman's diagram, hurricane-strength storms that generate current velocities of up to 121 cm/s are capable of initiating movement in average-sized nodules. Hurricanes have been estimated to directly affect South Florida only every five to eight years (Ball et al., 1967; Neumann et al., 1978), which suggests that physical transport of carbonate nodules occurs relatively infrequently. However, occasional pulses of scouring bottom currents have been observed on Florida's outer shelf and may occur in the area of nodule growth (Shinn, pers. comm.). In addition, nodules may roll at lower velocities than calculations suggest as a result of the low density of porous carbonate and the sail-like growth of macroalgae often found on top of nodules. Considering the results of calculations and sea-floor observations, Florida's outer shelf in the region of nodule growth is of relatively moderate to low energy, and nodule movement via physical processes probably occurs relatively infrequently. Because nodule-forming organisms grow relatively slowly (estimated at less than 2 mm/month) (coralline algae, Boscence, 1983), infrequent physical tranport via hurricanes or periodic surges could be sufficient to produce a nodular shape. However, because evidence suggests that only slight repositioning is needed for spheroidal growth, bio-induced nodule movements may be equally important to—if not more important than—infrequent physical rolling.

The abundance of sandy trails and nodule mounds within the nodule-rich region on Florida's outer shelf indicates that the sea-floor activity of the echinoderm *Meoma ventricosa* and the sand tilefish *Malacanthus plumieri* plays an important role in nodule movement. During its plow-like deposit-feeding, *Meoma* produces meandering, sandy trails in the surface sediment. In the production of these trails, nodules must be literally pushed aside in the disruption of the underlying or nearby sediments. *Meoma ventricosa* has been estimated to feed/move at a rate of 3–5 cm/hr (Chesher, 1969). An area of several 100 m², containing approximately 25 echinoids (a low population estimate with regard to qualitative observations on Florida's outer shelf) could therefore be reworked in less than one month.

Numerous concentrations of nodules are also found within

the mound-like nests of the sand tilefish, *Malacanthus plumieri*, hence the nest-building process itself is another avenue by which nodules may be frequently repositioned.

Although valid as a formative agent in many environments, physical transport may not always be the main or only means of nodule movement. Observations on Florida's outer shelf suggest that while physical movement of nodules probably occurs only every year or few years, bio-induced repositioning may occur on a monthly basis.

Fossil Interpretations

Results of this study indicate that in addition to shallow or physically turbulent environments, concentrically laminated nodules of $CaCO_3$ may form in relatively deep- and/or quiet-water conditions. Consequently, investigators of nodule-containing outcrops should consider all of the alternative depositional environments and processes that may play a role in nodule formation.

In fossil examples several lines of evidence may be examined to determine a nodule's mode of growth and depositional environment. The presence of sedimentary structures indicative of bedload transport, such as cross-bedding, or extensive rounding of individual grains, may indicate a dominance of physical processes. Signs of physical abrasion in well-preserved nodules (e.g., an apical growth response in branching rhodoliths) may also be indicative of energetic near-bottom flow. A quieter environment, characterized by biologic activity, may be revealed by an abundance of angular, biologically derived sediments, burrow or other trace structures, and concentrations of nodules in irregularly shaped and distributed lenses.

Evidence also suggests that where preserved, nodule morphology may be useful in interpreting a depositional environment. Nodules from Florida's outer shelf are primarily spheroidal in shape and their internal layers generally laminar in form. As previously suggested, this high degree of sphericity and laminar layering seems to correlate with relatively frequent repositioning. A lack of structural evidence in nodules for extended periods of growth in more than one direction also supports frequent movement. However, it should be recognized that frequency of movement in no way implies the physical intensity of such events. The sphericity of for-algaliths from Florida's outer shelf, a relatively low to moderate energy environment, is comparable to that of rhodoliths found in a relatively high energy environment (Fig. 7).

Many nodule-forming organisms are also thought to be depth-specific and therefore useful in paleodepth determinations (Adey, 1970), however, relatively few detailed studies have been undertaken in deeper-water environments. Those studies which have been conducted of deep-water nodules suggest that their ecology is a complex function of time, competition, and environment (Reid and Macintyre, 1988). Ecologic correlations between nodule communities and depth should therefore be made with caution. In conclusion, carbonate nodules may aid in paleoenvironmental reconstruction if deposits are examined by looking for large-scale depositional structures (e.g., cross-bedding) as well as small-scale features (e.g., grain angularity and nodule morphology).
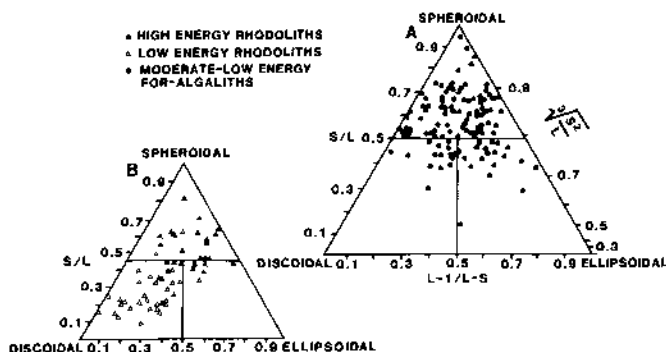

FIGURE 7—Comparison of nodule sphericity: A) moderate- to low-energy "for-algaliths," (this study), and B) high-energy rhodoliths (Boscence and Pedley, 1982).

QUESTIONS REMAINING AND FUTURE RESEARCH

Distribution

Results of this study indicate that nodule growth occurs only in a surprisingly limited and productive zone, concentrated in depths of 35–60 m on Florida's outer shelf. Although no explicit answer was found to explain the $1.2 \text{ km} \times 8.8 \text{ km}$ swath of nodule growth the authors believe that the local shelf features outlined below contribute to the production of environmental conditions conducive to nodule growth.

South of the southern limit of nodule growth, the continental shelf widens abruptly and protrudes farther into the Gulf stream than anywhere else along the reef tract (Fig. 2). Currents generally flowing to the north may be deflected or pass directly over this shelf bulge, causing abrupt attenuation of current velocities and upwelling within the zone of nodule growth. Upwelling, which often transports bottom waters rich in nutrients, may be a factor in producing conditions characterized by intense biologic activity. Additionally, extensive reef growth and accumulation of shallow-water sediments just west of the nodule zone may prevent the influx of turbid, nearshore waters onto the outer shelf. Lastly, the presence of an underlying topographic feature, yet unrecorded, may have influenced the development of the shelf's structure and seafloor conditions.

Growth Rate and Nodule Age

Although we were unable to determine the growth rate or age of nodules on Florida's outer shelf, they are expected to be similar if not younger in age than previously dated nodules from comparable regions. Radiocarbon dates of 400 ± 40 and $1,500 \pm 100$ years were measured for crusts and cores of living rhodoliths at depths of 63–66 m off the Canary Islands (McMaster and Conover, 1966). Assuming continuous growth, Adey and Macintyre (1973) estimated that deep water rhodoliths up to 30 cm in size could be as much as 800 years old. and Boscence (1983) estimated that with shallow-water, tropical growth rates (2 mm/month: Adey and Vassar, 1974), a 20 cm nodule with concentric growth could be up to 600 years old.

Other Types of Nodule Growth

Numerous other examples of concentric, biologically derived nodules exist worldwide, in both modern and ancient marine environments; yet their formation remains somewhat unexplained. Oncoids, presumably the product of sediment-trapping micro-organisms, are often found in relatively quiet-water environments. The processes by which oncoids form in these environments is not yet completely understood. In addition, the origin of deep-sea manganese nodules found in low-energy environments have for years been a matter of controversy. Could processes like those found on Florida's outer shelf, e.g., "circumferencial" growth and frequent bio-induced repositioning, explain the formation of other, unexplained examples of nodule growth?

CONCLUSIONS

1. Carbonate nodules are now forming on Florida's outer shelf in a surprisingly limited and productive zone, extending from south of Molasses Reef to south of The Elbow, in water depths of 35 to 60 m.
2. The majority of nodules are for-algaliths, containing an abundance of both encrusting foraminifera and coralline algae.
3. Because the growth of encrusting organisms occurs on all exposed nodule surfaces, only slight repositioning rather than complete overturning is necessary for nodular formation.
4. Nodule movement probably occurs (a) frequently as a result of bio-induced repositioning by the benthic activities of the echinoderm *Meoma ventricosa*, and the sand tilefish *Malacanthus plumieri*, and (b) infrequently via physical transport during surge events or hurricane-strength storms.
5. Carbonate nodule growth is not limited to shallow or turbulent conditions; therefore, evidence of deep- or quiet-water growth should be sought in the interpretation of nodule-containing deposits.

ACKNOWLEDGMENTS

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APPENDIX

CURRENT VELOCITY CALCULATIONS (37 M DEPTH)

	TROPICAL STORMS	HURRICANES
AVG. WINDSPEED	35 mph	75 mph
	(Ball et al., 1967)	(Neumann, 1967)
APPROX. DURATION	7 hrs	7 hrs
	(Wanless, pers. comm)	(Wanless, pers. comm)
WAVE HEIGHT*	9.5 ft	25.5 ft
WAVE PERIOD*	6.6 s	11.5 s
CURRENT VELOCITY**	0.43 ft/s (13 cm/s)	3.99 ft/s (121 cm/s)

*Based on Deepwater Wave Forecasting Curves of the U.S. Army of Coastal Engineers (1977).

**Calculated using: $(U_{max} (-d)/H = \pi/\sinh$, as derived from The Small Amplitude Theory (U.S. Army Coastal Engineers, 1977); $U_{max} (-d) =$ Maximum bottom particle velocity, $T =$ Wave period, $H =$ Wave height, $h =$ Tidal range, $L =$ Wavelength and $d =$ depth.